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6. AUTHOR(S)

Dr. V.L. Semenov

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Central Institute of Aviatin Mortos (CIAM)
Aviamotornaya St., 2
Moscow 111250
Russia

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CENTRAL INSTITUTE OF AVIATION MOTORS

Technical Report № 4

THE POSSIBILITY INVESTIGATION OF STRUT FUEL FEED SYSTEM USE IN SCRAMJET COMBUSTORS ON RESULTS OF TESTS WITH HYDROCARBON FUEL

FINAL REPORT

EOARD Order
No F6170896W0221

Project Leader
Dr. V.L. Semenov

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Abstract

The presented final report contains the summary of the results of three previous stages of serviceability investigation of strut fuel feed system intended to inject fuel into supersonic high-enthalpy flow of two-dimensional small-scale model scramjet combustor.

The results of the fourth stage of the work on EOARD Order No F6170896W0221 are presented in section concerning fuel strut thermal state in free supersonic flow investigation. This strut is designed, manufactured and tested in accordance with modeling concept and studies methodology taking into account results of the first three stages. The strut is intended for the following bench investigations of combustion and heat exchange problems in duct of combustor burning hydrocarbon fuels of various types, injected chiefly in gaseous phase. This strut dimensions differ from dimensions of earlier tested struts. They correspond to the scale of scramjet module for flying test beds of the second generation of "IGLA" type.

The final section of the report incorporates the results generalization of model studies of combustor operating process and fuel struts cooling system and the recommendations on these results use in the cases that combustor of different sizes burning different types of fuels operates.

Contents

Introduction

The initial stage of experimental verification of one of two competing schemes of scramjet combustor operating process realization is shown in present paper in the form of the results generalization of bench tests of small-scale combustors and autonomous module with strut fuel feed. The benefit of small-size scramjet combustor use in propulsions of various hypersonic flying vehicles depends to a great extent on engine design and on the extent of its integration with vehicle. The gain in fuel economy and flight distance can reach 14% and 25% respectively in comparison with supersonic ramjet use as a part of propulsion at flight Mach number $M_f \geq 4.5$ and ram value q=75kPa. The gain can be increased with ram value increase and flight Mach number increase up to M_f=8-10 under condition of optimal control of air-fuel ratio in the combustor. The revealed possibility to recalculate model tests results for full-scale combustors (including the applicability of obtained operation limits of strut fuel feed system, and cooling system of the most critical elements, i.e. struts leading edges) determine the usefulness of the studies have been carried out. The interest to hydrocarbon fuels use is aroused not only by their high density and corresponding reduction of fuel tanks volume but also by revealed in the last studies [1] possibility to use gaseous phase of mixed and endothermic aviation fuels in cooling system, significantly extending the operation range of scramjet for propulsions of hypersonic vehicles of various purposes.

1. **Summary of the main results obtained in the three first stages of model tests.**

The first stage of work was devoted to the data generalization of experimental studies of ignition and combustion stabilization in model combustors with various tubular struts for fuel feed. On the base of investigations of the flow around separate struts with fuel injection normally to the main flow and considering thermovision pictures of side wall heating and static pressure distribution along side wall, an approximate model of combustor operating process was constructed. In agreement with this model, the empirical criteria of ignition and burning stabilization are proposed. The limits of these criteria validity for two-dimensional combustor of one-sided expansion are obtained.

The results obtained in tests of combustors with connected pipe are corroborated by tests of autonomous module in free stream with $M_\infty=5.6$. The module consisted of three-shock inlet combustor with five echeloned struts and shortened nozzle. The fuel in use — T-1 kerosene saturated by air (2% on mass). Ram value corresponded to 50 kPa. Incoming flow total temperature $T^*=1300\text{-}1480K$, air-fuel excess (equivalence) ratio $\alpha=1.32\text{-}1.76$ [2].

The second stage of work was devoted to the conditions of strut fuel feed system use in full-scale engines and to their simulation in ground test facilities and at hypersonic flying test beds. Serviceability limits of strut fuel feed system were considered with taking into account combustor operating process realization and critical elements cooling organization with use of various working media.

Several zones of realizable combustion modes for two-dimensional combustor with one-sided expansion are revealed depending on fuel flow rate per unit of combustor cross-section in injection section, and air-fuel equivalence ratio. On the base of analysis of model struts operating, the serviceability limits of regenerative system for cooling leading edge of fuel struts are obtained. They are: for kerosene — $M_f \leq 7$, and $M_f \leq 10$ — for hydrogen [3].

The third stage presented the methodology development of investigating large-scale model strut with impingement-jet cooling of leading edge with use of special equipment for leading edge thermal state study in free stream at incoming flow parameters: Mach number $M_\infty=2.5$, total temperature $T^*=800\text{-}1500K$ [4].

In addition to tests of conditions of simulating, scaling and data processing methods, the empirical dependencies for heat input into and removal from the leading edge, which permit to estimate materials and structures serviceability at heat flux into leading edge $q \doteq 8\text{-}20 mW/m^2$, are verified.

2. Heat state of different struts with impingement-jet cooling by air and methane

The present stage of investigations was planned to define the peculiarities of the recalculation of the heat state of the fuel strut flown over by free supersonic jet of high-enthalpy gas when different coolant are used. Besides, the new strut of modernized structure was investigated (see Fig.1), in addition to the strut had used at previous stage [4]. The development, design, and production of this strut, intended for the future model scramjet research were ones of the main goals of the investigation. The structure and main dimensions of this new strut are presented below in this section. However, this strut had rather small size and detailed investigation of its heat state was much complicated. Thus the main results were provided by investigation of large-scale strut, which structure and dimensions were described in report on 3-nd stage of current order [4]. At this stage the test bench was modernized to perform the switching from air-coolant to methane and vice versa.

The test schedule was the following:

- the air-coolant was feeding to strut and the fire heater was starting and going to the steady mode (the technique of the test bench starting is described in detail in previous report [4]);
- the valve of methane supply was opened on;
- the valve of air supply was closed off;
- after the steady-state wall temperature mode obtaining at pure methane supply the fuel feed was switching to air by reverse sequence;
- the new level of hot flow temperature was established at strut cooling by air and after setting of new steady state conditions the cycle of switching was repeated;
- after performing of the necessary mode set the test bench was switching off.

The use of such schedule with air-methane switching reduced the cost of tests because of the decrease of methane consumption. Besides, just this sequence of actions is planning to be used at fire tests of struts inside the model scramjet combustion chamber at the investigation of the ignition and combustion processes. The typical varying of the main temperatures and pressures during the test with air-methane switching are presented at Fig.2,3. The characteristic change (decrease) of wall temperature after transition to methane is seen. The change of cooling regime at the transition is connected with change of coolant flow rate as well as the change of coolant physical properties. The peaks of pressure at the switching moments connected with the simultaneous supply of both coolants. However, there is not significant response of the wall temperature to such short-time flow rate peaks, because of the heat inertia of wall.

The main goal of the experimental data processing was the establishing of the additional regularities connected with the influence of coolant fluid properties at jet-impingement cooling. The necessity of such investigation is caused by the following. It is known that the main parameter, described the

heat transfer at the coolant side, that is the Nusselt number, depends on such general set of similarity criteria:

$$Nu = f\,(X/L,\ Re,\ Pr,\ T_w/T,\ \mu_w/\mu,\ \lambda_w/\lambda,\ C_w/C), \qquad (1)$$

where X/L - dimensional factor, Re - Reynolds number, Pr - Prandtl number, T_w/T - temperature factor (T_w - wall temperature, T - character flow temperature), μ_w/μ – ratio of viscosity coefficients, λ_w/λ – ratio of heat conductivity coefficients, C_w/C - heat capacity ratio.

The last four parameters in (1) are necessary to take into account the varying of the physical properties of the fluid across boundary layer when its temperature is varying from the one of the flow core to wall temperature. In many cases this influence usually may be written by rather simple power functions such as:

$$Nu = a\cdot Re^{n1}\cdot Pr^{n2}\cdot(T_w/T)^{n3}\cdot(\mu_w/\mu)^{n4}\cdot(\lambda_w/\lambda)^{n5}\cdot(C_w/C)^{n6} \qquad (2)$$

If the particular fluid at reasonable temperature range is considered, the ratios of properties (viscosity, heat conductivity and heat capacity) may be described as power functions of temperature factor itself. The Prandtl number for gaseous fluids are practically constant. Then the dependency (2) for such conditions may be significantly simplified:

$$Nu = a\cdot Re^{n1}\cdot (T_w/T)^{N3} \qquad (3)$$

Just such equation (a=3.4, n1=0.412, N3=1.25) was obtained at the processing of the test data at the 3-d stage of contract by order [4], when only air-coolant was used. The strong dependence of Nusselt number on temperature factor may be noted separately. Evidently this is caused by the choice of the characteristic temperature for calculation of physical properties that was the inlet temperature of coolant at the entrance to strut. If the characteristic temperature were some average between inlet one and wall one, then the exponent N3 would decrease significantly. The reason of such tendency is connected with influence of temperature trend of viscosity/heat-conductivity, that are contained in Re and Pr numbers correspondingly. However, the choice of the inlet temperature as characteristic one is more useful. Moreover, the generally accepted technique for choice of such temperature at jet-impingement has not justified yet, though the integral-mass-average value is obviously used for ordinary flows

When the cool agent is changed, the possibility of use of the incomplete criteria dependencies such as (3), obtained for other fluid, is determined by the level of compatibility of the Prandtl number and temperature trends of viscosity/heat-conductivity/heat-capacity. It is known that the exponents at power functions, that approximated the viscosity/heat-conductivity dependencies on temperature for diatomic gases (nitrogen, oxygen, hydrogen, air etc.) are closed to each other:

$$\mu_w/\mu,\ \lambda_w/\lambda \approx (T_w/T)^{N4}, \quad \text{where } N4 \approx 0.7...0.9 \qquad (4)$$

Prandtl numbers of such gases may be considered as constant at rather broad range of temperatures (at sufficiently high average temperature level in comparison with critical one). Thus the dependence (3) may be used directly at transition to hydrogen-coolant, for instance.

However, the multiatomic gases such as methane CH_4 and other heavy hydrocarbons may reveal essentially deviant dependencies of above-considered properties. In particular, for methane in temperature range $T, T_w = 250...550$ K:

$$\mu_w/\mu \approx (T_w/T)^{0.79} \quad , \quad \lambda_w/\lambda \approx (T_w/T)^{1.3} \qquad (5,6)$$

Heat capacity of methane at this temperature range is less changed (by ~1.5 times), whereas Prandtl number at such temperatures stays close to its value for air ($Pr \approx 0.73...0.76$). Thus, at the transition from air to methane it seems the most important to take into account the change of temperature trend of heat conductivity by introduction of additional terms into the criteria equation for Nusselt number.

The processing of the primary experimental data was carried out by use of technique, described more detailed in previous report [4]. All main assumptions and factors to take into account were conserved. This technique had provided the good agreement of experimental data for previous research and it may be used without any changes for current stage at least for air-coolant. However, after the transition to methane the analysis of the processed experimental data had confirmed the necessity of above-mentioned transformation of criteria dependencies. To illustrate this, the evaluation of experimental heat fluxes at the transition to methane by use of the initial dependence (3) is shown at Fig.4 for one of the tests. One can see that the divergence between hot-side and cold-side heat fluxes. Evidently such divergence was absent at air-cooling mode. To eliminate mentioned divergence the dependence (3) was appended by multiplying coefficient to take into account the influence of heat-conductivity:

$$Nu = a \cdot Re^{n1} \cdot (T_w/T)^{N5} \cdot (\lambda_w/\lambda)^{N6} \qquad (7)$$

The regression analysis had shown that the best agreement of hot/cold heat fluxes for both methane and air may be obtained at

$$N6 = -0.85, \quad N5 = 1.98$$

It should be mentioned that this dependence is fully adequate to initial for air, i.e. after the installation of real power function for air heat-conductivity

$$(\lambda_w/\lambda)_{air} \approx (T_w/T)^{0.859}$$

the dependence (7) simply transforms into dependence (3).

The results of test data processing by use of dependence (7) are presented at Fig.4,5, where one can see good agreement between hot/cold side heat fluxes at leading edge of strut.

Further tests were carried out after installation of new strut at the test bench. This strut had been manufactured by CIAM production factory. The internal structure and main sizes of strut are presented at Fig.1 (see also photography at Fig.6c). The manufacture procedure process consisted of three main stages.

At the first stage the inclined channells were milled in two flat plates. When these plates were joined together by vacuum brazing, the ribs between milled grooves formed the internal channels (see Fig.1 and photography at Fig.6a). These channels are intended for fuel supply to the injecting nozzles

and to the nozzles of jet-impingement cooling of leading edge. The connected plates also form the strength framework of the strut. The contoured orifices (coolant nozzles) were drilled in the front face of the connected plates to provide jet-impingement cooling of the leading surface (nozzle diameter d=0.25mm, nozzle number N=19). At the second stage of manufacture the horizontal channels (grooves) were milled in external surface of connected plates (see Fig.1 and photography at Fig.6b). These channels when covered by sheath are used for carrying away of fuel after cooling of the leading edge, thus the external cooling ducts were organized. At the third stage the specially stamped sheath was snugly pulled over the rigid framework. The sheath is made of high-temperature steel sheet of 0.25 mm thickness. The sheet was U-shaped by bending, thus the leading edge had the external diameter D=3.5 mm. The angle of edge inclination to strut base and to flow direction was 45°. The sheath was connected with the framework by special vacuum blazing at external surfaces of ribs between external cooling channels. Then the orifices (injection nozzles) were drilled throughout the sheath and ribs into internal channels. This nozzles are intended for fuel injection into air at normal direction to its flow. The other part of fuel, had used for leading edge cooling, cooled the side surface of the strut, while flowing through external channels, and then injected from the rear of the strut downstream air flow. At the forth stage of manufacture the framework, covered by sheath, was brazed to the strut base. This strut base had two cavities connected correspondingly with channels of fuel supply to leading edge and to the injection nozzles. These cavities were fed by two individual unions of fuel supply.

The test stage, that used this new above-described strut had not aimed to obtain much of scientific results, but should confirm the serviceability of the new strut structure. This strut had smaller size, including the height, that was 45 mm and it is about two times lower than previous strut. Then, to eliminate the influence of earlier identified boundary layer the new strut was mounted by such manner that its blade was out of it, i.e. in uniform core of jet. The root section of strut blade was at 25 mm above the plate of bottom wall of rectangular exhaust nozzle. The gap between the installation plate, extended the mentioned bottom nozzle wall, and strut base with feeding unions was protected by the blast shield, that swing the gap flow downward-and-aside, thus its possible action on strut edge was practically eliminated. The leading edge of this strut was equipped by two thermocouples, whereas the position of one of them (the lower one) corresponded to the jet point in which the middle thermocouple was positioned at the testing of previous strut. It should be mentioned that the measurement of the coolant heating inside strut cooling ducts was not carried out, because of the main goal of tests was the checking of serviceability not global research.

The flow rates of methane throughout cooling circuit and circuit of normal fuel injection correspond to the operation level, planning for its work in model combustion chamber. The main parameters of tests, had been carried out, are presented in Table 1.

It should be noted, that some changes of the strut internal structure may and do lead to some varying of the cooling performances and changing of the coefficients in Nusselt number dependencies on governing criteria. The detailed investigation of this divergence was not carried out and the serviceability of this strut was calculationally checked by use of equation (7) taking into account the geometrical parameters of new strut, that are involved into used criteria. The calculation and experimental values of wall temperature for one of tests are presented at Fig.7. It is seen that the agreement between them is sufficient for engineering evaluation. The main tendencies are qualitatively true and quantitatively the average error of evaluation is in limits of ±5%.

Finally, the carried out research on heat state of scramjet fuel struts had experimentally confirmed the high level of serviceability of two types of struts with jet-impingement cooling by air and methane. The calculation and test technique for research of cooling performances of struts was developed and verified. The obtained criteria dependencies of Nusselt number on Reynolds number, temperature factor and heat-conductivity ratio may be used for the evaluation of the leading edge temperatures with internal jet-impingement cooling at least for the structures closed to investigated. The revealed influence of heat-conductivity at jet-impingement cooling had not been reported earlier in available sources. The heat state and cooling performances of investigated struts make possible their installation in scramjet combustion chamber as fuel injectors for investigation of ignition and combustion processes.

Table 1

T* [K]	P* [ata]	M	Coolant	G [kg/s]	Tw [K]
1140	23,6	2,51	Air	1,9E-02	935
1140	23,6	2,51	Air	2,5E-02	925
1140	23,6	2,51	Methane	3,6E-02	830
1140	23,6	2,51	Methane	2,8E-02	855
1040	22,0	2,51	Air	1,8E-02	860
1040	22,0	2,51	Air	2,4E-02	850
1040	22,0	2,51	Methane	3,5E-02	810
1040	22,0	2,51	Methane	2,6E-02	845

3. Obtained results generalization and the recommendations on strut fuel feed system feasibility in scramjet combustor.

The results of experimental studies of fuel injectors geometry influence on combustion parameters and modes are presented in Fig.8 in the form of static pressure distribution along combustor side wall axis. These results correspond to Mach number at model combustor entrance $M_{entr}=2.5$. On the abscissa the distance from combustor entrance divided by the height of combustor entrance cross-section is plotted, and the ordinate is static pressure divided by total pressure in heater.

All characteristic operation modes realized in common flow passage for four various fuel struts are presented in Fig.8. This is made both to emphasize significant effect of injection geometry and make more convenient modes considering. The similar set of operation modes on result of module tests in external flow is difficult for understanding because of superimposing of one static pressure distribution on the other. For Fig.9 presenting tests data processing results, characteristic operation modes with subsonic. transonic and supersonic combustion are chosen.

So, the results obtained with injection of kerosene saturated by adding 2% of air (on mass) injection normally to the flow are shown in Fig.8.

Curve 1 in this figure presents pressure distribution at subsonic combustion due to flow "choking" by air jet throttling at combustor exit. Three (3) struts are positioned frontally, four orifices 0.34mm in diameter are made in every side wall. Injectors positioning between struts is symmetrical.

Curve 2 presents pressure distribution at supersonic flow deceleration to M=1 through pseudoshock in combustor flow passage without struts but with heating up to 2200K, i.e. it represents ideal combustion at $\alpha\sim1$ in supersonic (in the average) flow (recalculated according to [5]).

Curve 3 presents subsonic combustion of almost 50% of fuel in injection zone and then its afterburning in accelerating flow in duct with 6 struts positioned frontally, in which 18 orifices are made symmetrically.

Curve 4 presents fuel burning in transonic flow in duct with 3 struts positioned with echeloning, in which 24 fuel orifices 0.34mm in diameter are made. Mutual position of orifices of neighboring strut is staggered. Strut spacing is taken from the requirement that shock wave from base of one strut do not tall on neighboring strut. The angle of strut leading edge inclination is 45^0.

Curve 5 represent supersonic combustion mode in flow passage with 5 echeloned (significantly) struts with symmetrical positioning of 6 orifices on every strut (3 orifices on every side). The similar system was used in autonomous module combustor and was successfully tested at air-fuel equivalence ratio in the range $\alpha=1.32-1.76$.

Fig.9. shows flow Mach number and local combustion efficiency distribution along combustor flow passage for three characteristic combustion mode: subsonic, transonic and supersonic to which numbers

3,4,5 respectively correspond. Combustion efficiency for echeloned struts is taken at the same length of combustor.

Curves 6 - present the stages of operation preparing and initiation (ignition) with use of pneumatic throttling. The data presented in [2] show that combustor starting with use of air-jet throttling in the end of supersonic combustor (in the presence of gas heater burning kerosene, methane or hydrogen) can be realized without ignition source at total temperature at the entrance in the range from 1050 till 1320K. It should be expected that this limit can be shifted to 1320-1440K with pure air use (on supersonic ramjet development experience [6]). The mentioned experience of supersonic ramjet development and the experience of dual-mode scramjet for "Kholod" HFTB development show that ignition in high speed combustor with use of low-power source is possible at incoming flow total temperature T^*=100-800K with pure air use or under flight condition, if fuel feed is organized correctly.

Thus, on the base of the data presented in reports [2,3,4] the analysis and made above comments to Fig.8, it is possible to make the following generalization and the recommendations on design of strut fuel feed system for high-speed combustors:

1. Engine type and flow passage geometry corresponding to scramjet or dual mode scramjet can be chosen depending on flight velocity range appropriate to hypersonic flying vehicle flight program. The second type engine has necessarily to be fitted with forced ignition unit.

2. The type of fuel feed struts positioning in combustor has to be chosen depending the range of air-fuel equivalence ratio control:

- frontal struts positioning with staggered injectors positioning has to be used for narrow range;

- echeloned struts positioning with symmetrical disposition of fuel nozzles for creation of nodes of intersections of shock waves caused by fuel injection has to be used for wide range;

3. For hydrocarbon fuel burning and engines operating in flight velocity range corresponding to $M_f \leq 6$- 8, normal (perpendicular) to incoming flow injection is preferable.

4. To improve preparing hydrocarbon fuel injected in liquid phase, its saturation by air or hydrogen (2% on mass) is necessary.

5. To ensure stable ignition in scramjet combustor at Mach number range of 3.5-5.5, temporally throat creation at combustor exit is necessary. This throat has to be from 70 to 50% of cross section of combustor exit.

6. The expansion angles of combustor flow passage sections depend on operation range on Mach number, struts disposition type, local fuel flow rate per unit of combustor cross-sectional area (see [3],) and necessary thrust (β_1=4.5 - 7°; β_2=1 - 4°)..

The same recommendations can be applied to cross-sectional area ratios for corresponding sections of combustor in the range from 1.2 till 1.5 and from 1.5 to 1.85.

7. Combustion efficiency depends on operation mode and type of injection struts greed. If the struts are positioned with echeloning, the same

combustion efficiency, as in the case of frontal positioning of struts can be attained with use of the longer combustor (by 20%). It should be noted here that engine cycle efficiency has to be determined for the combustor together with exhaust nozzle [8].

8. "Rough" model of operating process with generation of combustion macrozone in the center of a combustor, empirical criteria of ignition and combustion stability with parameters estimation according to one-dimensional procedure [7] can be applied to flight Mach number in the range M_f=5.6-8 at normal to flow fuel injection.

9. Strut fuel feed system serviceability in high-enthalpy flow is determined by heat resistance of strut leading edge and thermophysical properties of the fuel.

In accordance with the above presented recommendations on modeling, the section of scramjet combustor flow passage was designed and manufactured to investigate operation performances of perspective hydrocarbon fuels (Fig.10.).

Fuel feed system of this section incorporates:

- small pilot strut for forced plasma ignition unit positioned with axis of long side of rectangular combustor cross section;
- two struts for fuel injecting normally to flow fitted with impingement-jet cooling of leading edge and regenerative cooling of side walls (the struts are positioned on axes of short sides of combustor cross section at a distance of 60-75mm from pilot flame).

To check the recommendations validity, fuel feed system is designed and flow passage of axisymmetrical dual mode scramjet for "Kholod" HFTB (Fig.11) is modified (recontoured) for burning methane or isooctane which are preliminary saturated in rear support struts, then they are heated in cooling jacket (fuel is used as a coolant) and injected into combustor. In this case, "Kholod" HFTB can reach flight velocity corresponding to M_f=7(without hydrogen tank, see Fig.11.

The other example is three-module two-dimensional scramjet designed for "IGLA" HFTB (Fig.12), where the fuel struts designed for gaseous phase of hydrocarbon fuel have to be mounted. As the same tank volume can be filled with 220kg of hydrocarbon fuel instead of 17 kg of liquid hydrocarbon, it is possible to say about active flight of hypersonic flying vehicle with defined distance instead of equilibrium gliding. Engine performances and flight distance estimates are carried out for JP-7, methane, isooctane and nonane. The results obtained for nonane and presented in the Table 2 are of particular interest. They revealed maximal flight distance and optimal Mach number of cruise flight (1257km and M_f=8 for Hypersonic flying vehicle with initial mass of 2000kg).

Conclusion

Computation-experimental investigations of the possibility to use the strut fuel feed system for hydrocarbon fuel injection into scramjet combustor were carried out by testing of model combustors with connected pipe and in autonomous experimental module flowed over by free stream. This research has revealed the good reproducibility of the results in investigated range of main parameters (Mach number before combustor M_∞=2.5-5.6, total temperature T^*=1100-1870K, total pressure P^*=20-29 kPa, fuel flow rate G=20-60 g/s, air-fuel equivalence ratio α=1.1-2.2) and permits to obtain the operation domain boundaries.

The recommendations on design of strut fuel feed system for full-scale scramjets have been developed and the criteria of strut fuel feed system applicability in the range of flight Mach number M_f=3.5-8 at ram value $q_{max} \leq 75$ kPa has been obtained. The thermal investigation of tubular struts with coolant flow along leading edge inside round channels has shown the limit flight Mach numbers for normal operation of strut at ram values $q \leq 50$kPa, that are $M_f \leq 7$ for kerosene and $M \leq 10$ for hydrogen. This fact has determined the necessity of transition to impingement-jet cooling of leading edge.

The investigations of the thermal state of model struts with impingment-jet internal cooling of leading edges (two various structures with leading edge diameters of 6.7 and 3.5mm, both being cooled by methane and air) have corroborated their high serviceability at autonomous testing in free supersonic jet of high-enthalpy gas (total pressure P^*=22-24ata, total temperature T^*=800-1500K, Mach number M=2.5, wall temperature T_w=750-1000K, specific heat flux q=8-20 MW/m^2).

Experimental and computation technique for estimation of strut cooling performances has been developed and verified. Obtained criterial dependence of Nusselt number at impingement-jet cooling on Reynolds number, temperature factor and heat conductivity ratio

$$Nu=3.4 \cdot Re^{0.412} \cdot (T_w/T)^{1.98} \cdot (\lambda_w/\lambda)^{-0.85}$$

permits to estimate the heat flux values and wall temperature of strut leading edges with accuracy that is sufficient for engineer purposes (up to 10-15%) at least for structures that are similar with investigated ones. The revealed heat conductivity influence on performances of impingement-jet cooling have not been reported earlier in sources known to authors.

Semenov V.L.
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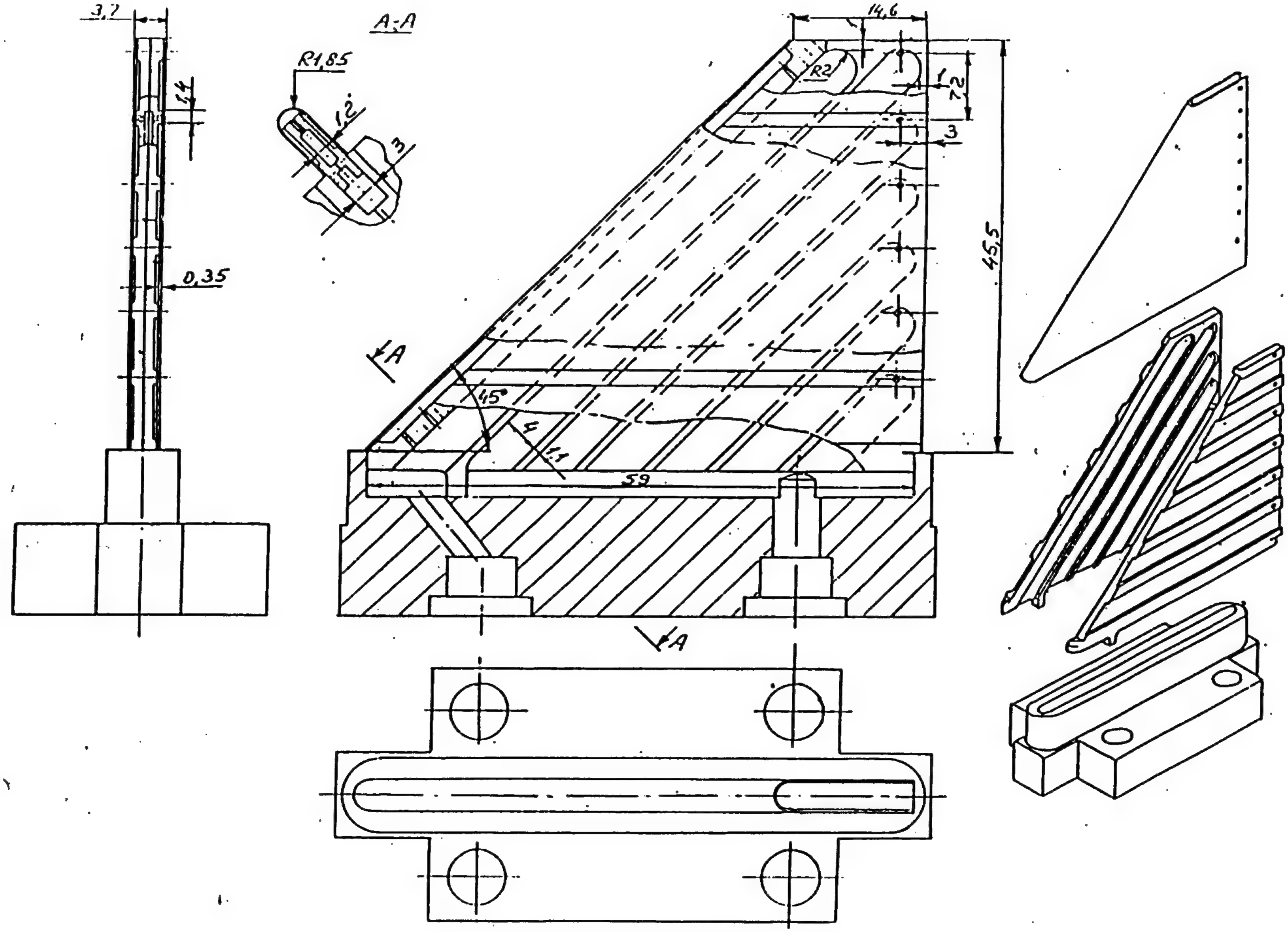


Fig. 1 Universal fuel injection strut for hydrocarbon fuel

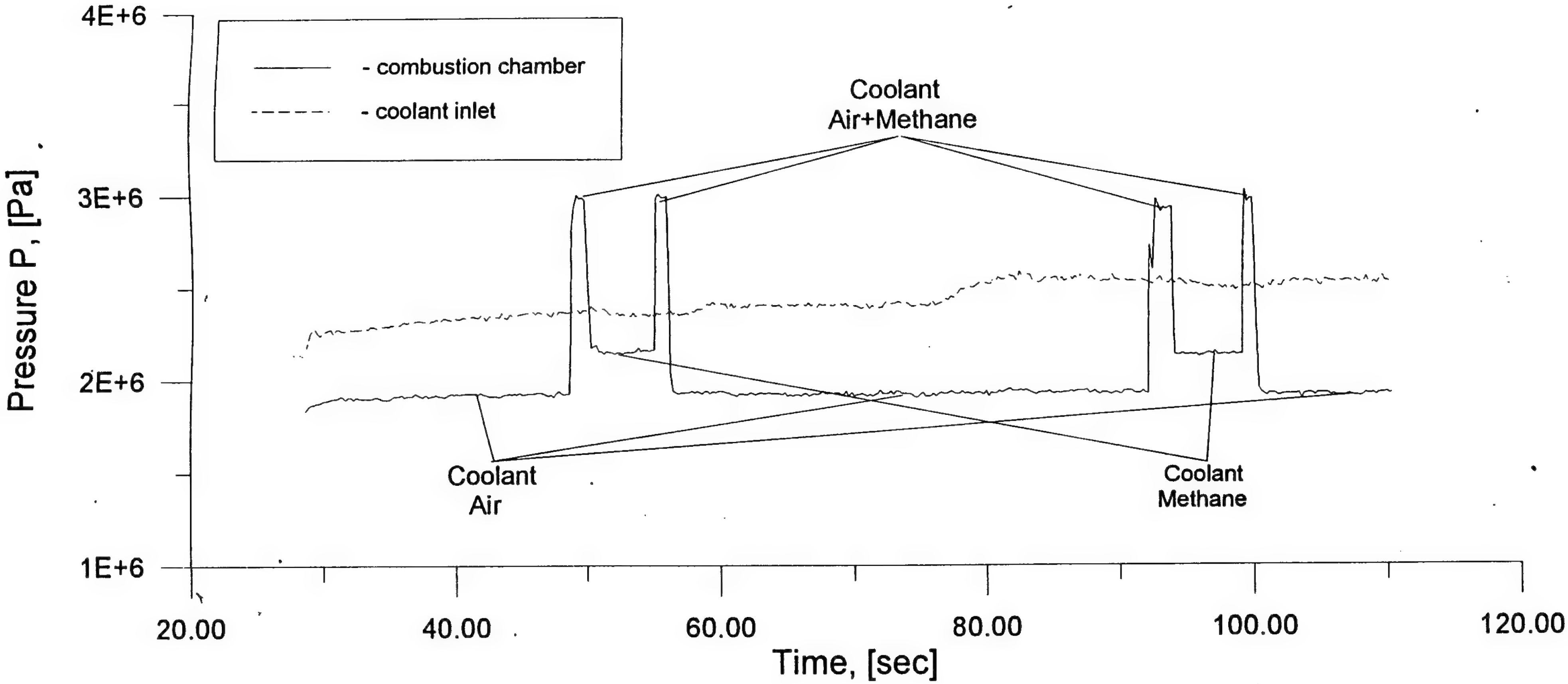


Fig. 2 Pressure in combustion chamber and pressure at inlet of cool agent into strut at tests with switching air/methane coolagents.

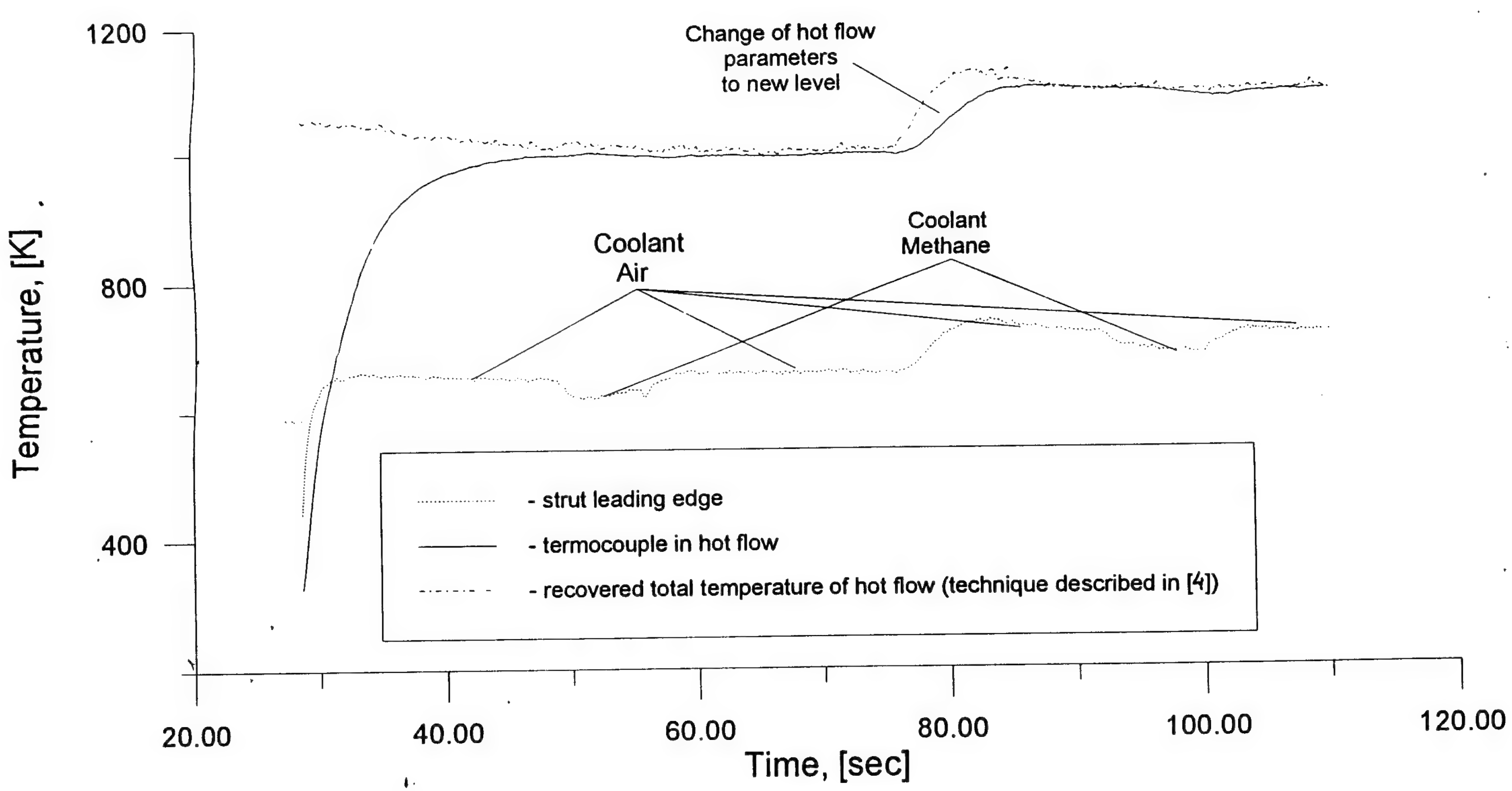


Fig. 3 Different measured temperatures during test with switching of coolant.

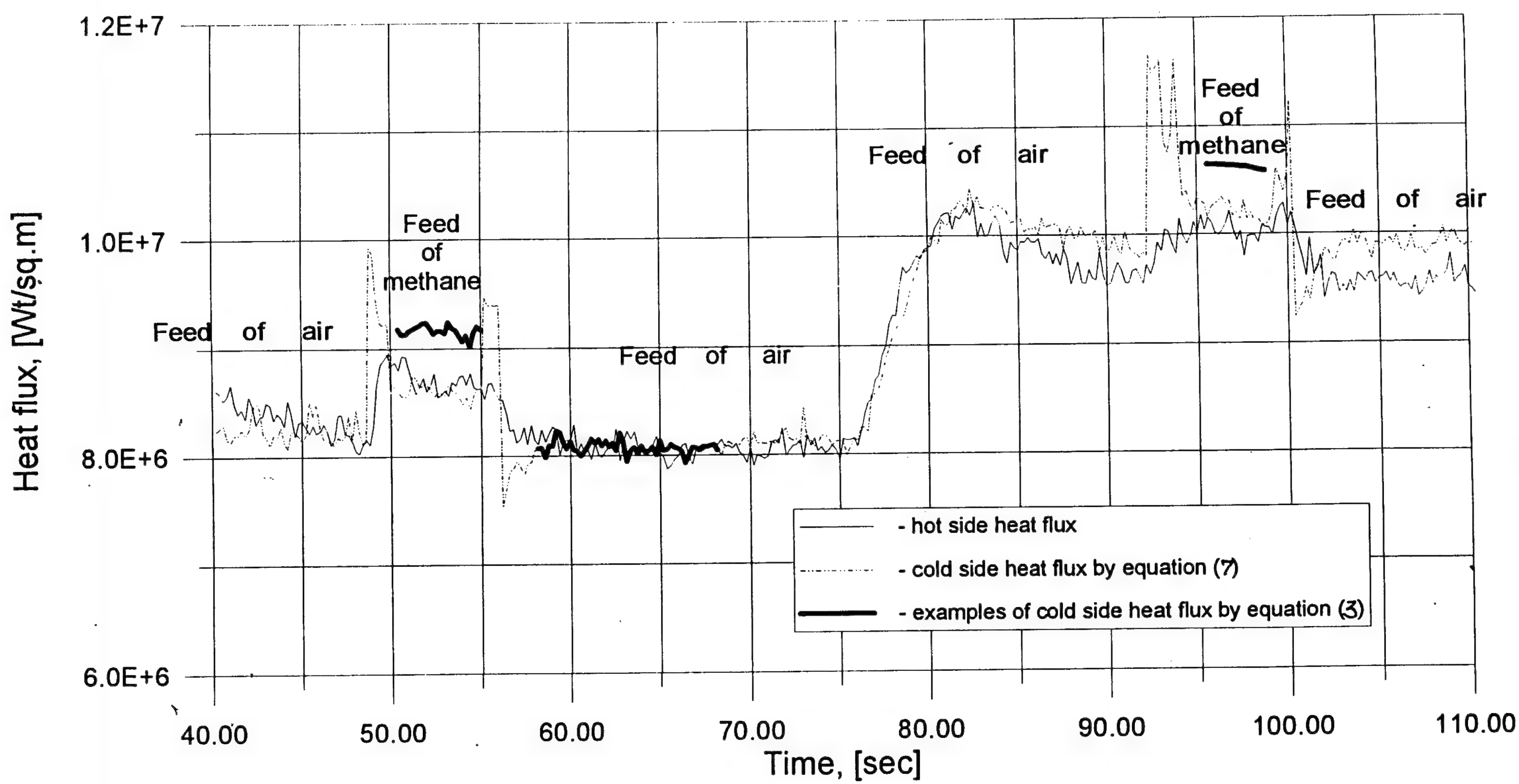


Fig.4 Heat fluxes at cold and hot sides of strut wall at leading edge (Exp A).

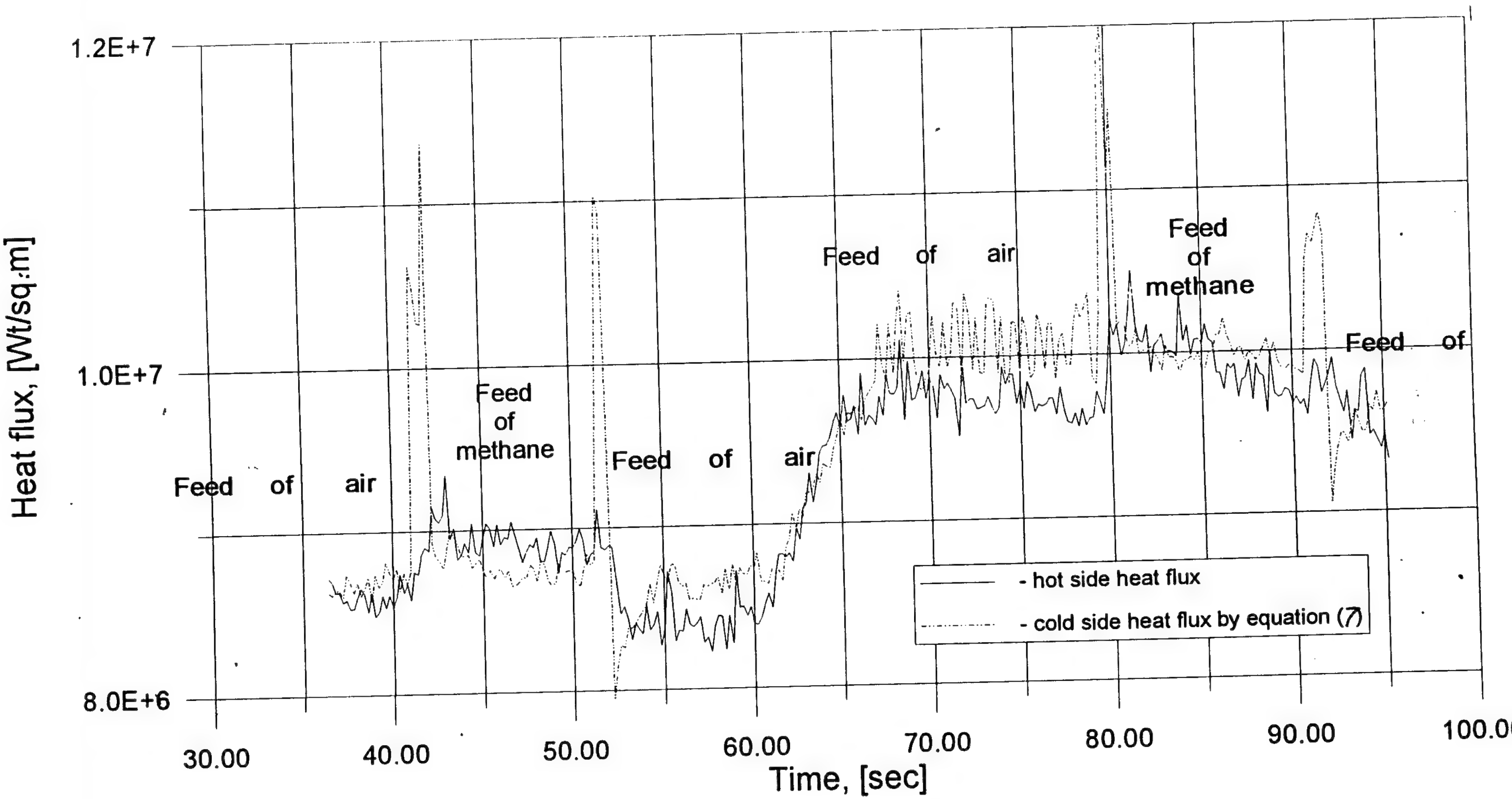


Fig.5 Heat fluxes at cold and hot sides of strut wall at leading edge (Exp B).

a

b

c

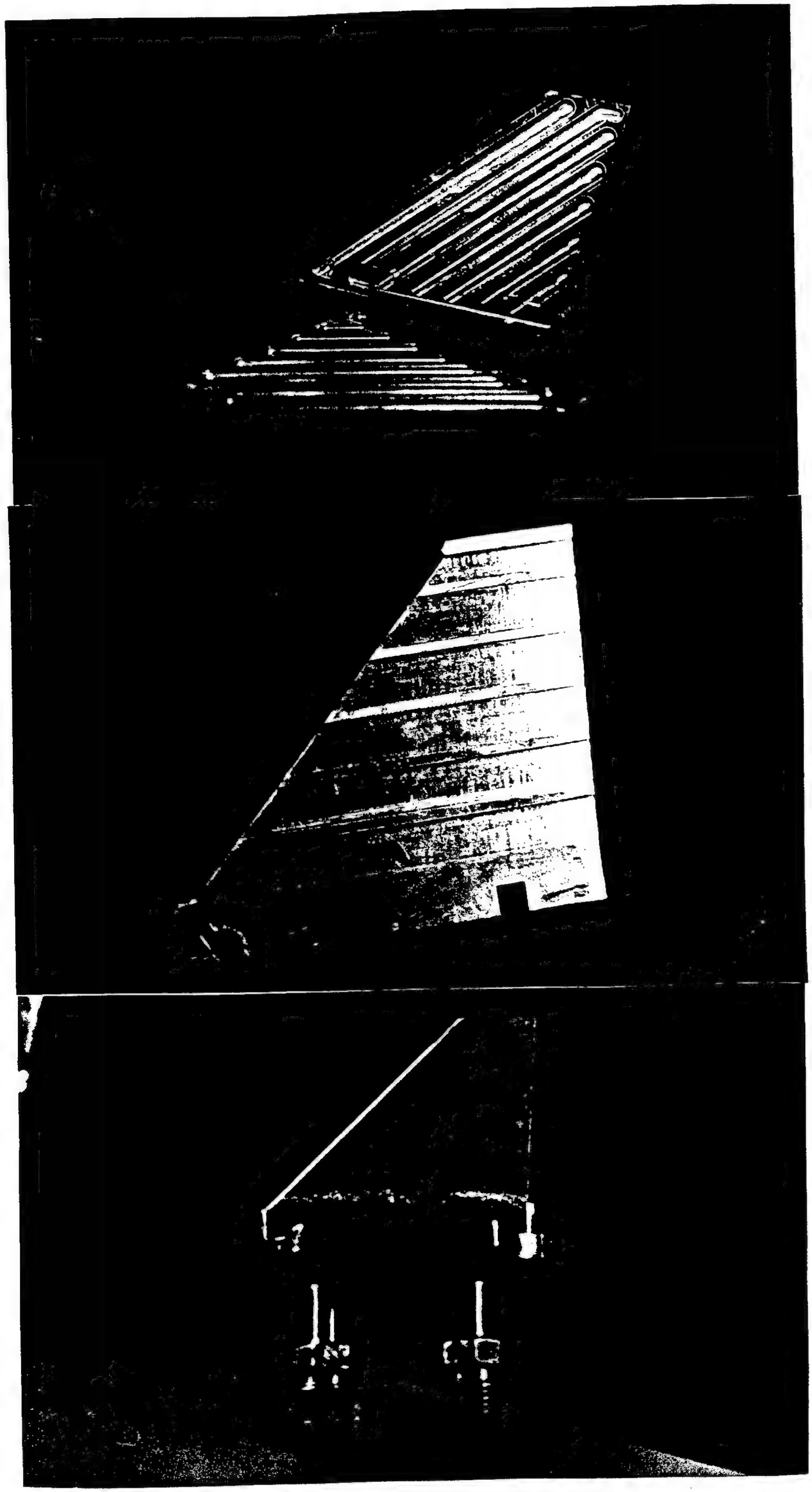


Fig.6. Photographs of fuel strut at various stages of manufacture

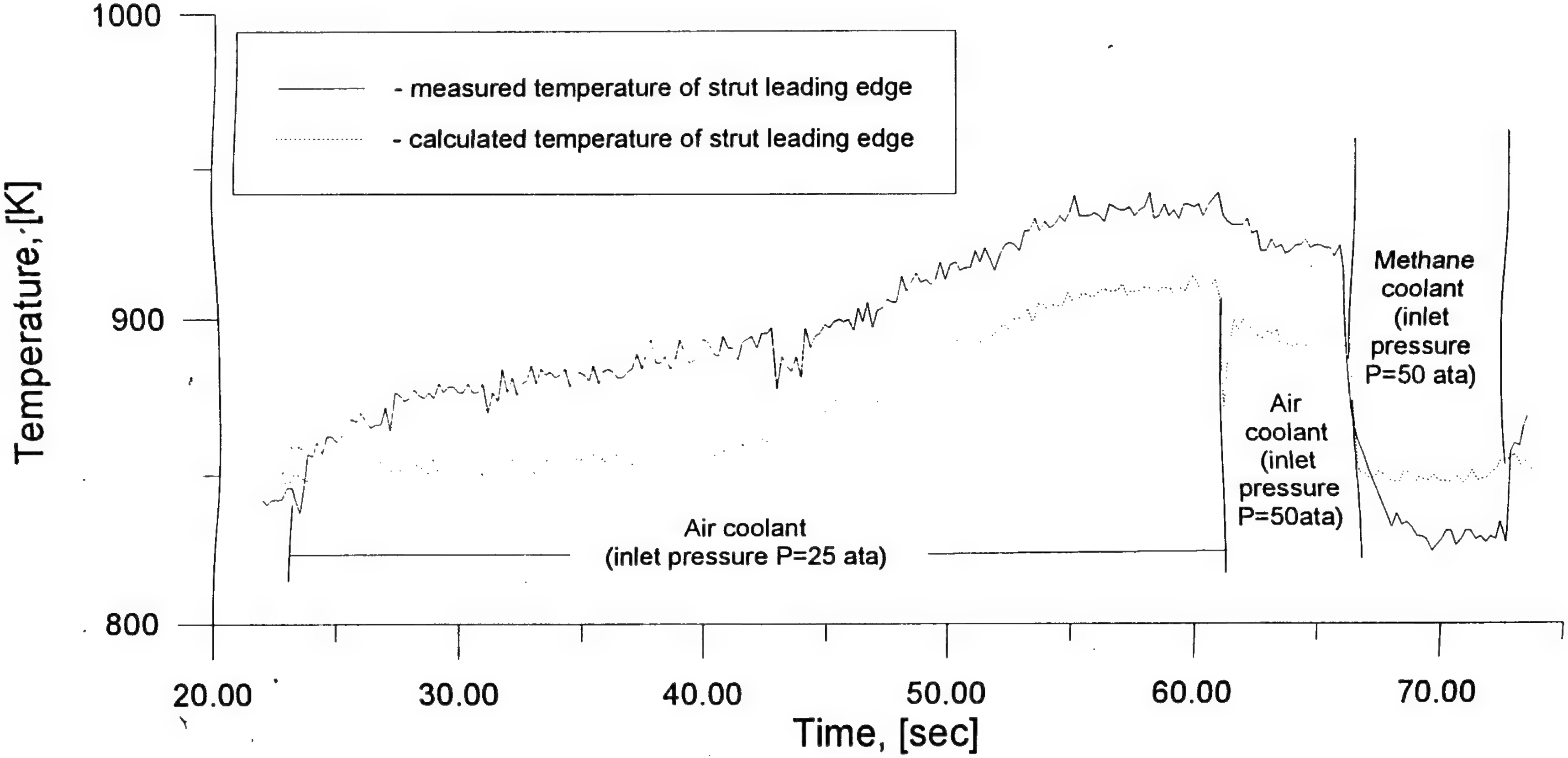


Fig. 7 Measured and calculated temperatures of strut leading edge for modernized strut at tests with switching of air/methane coolant.

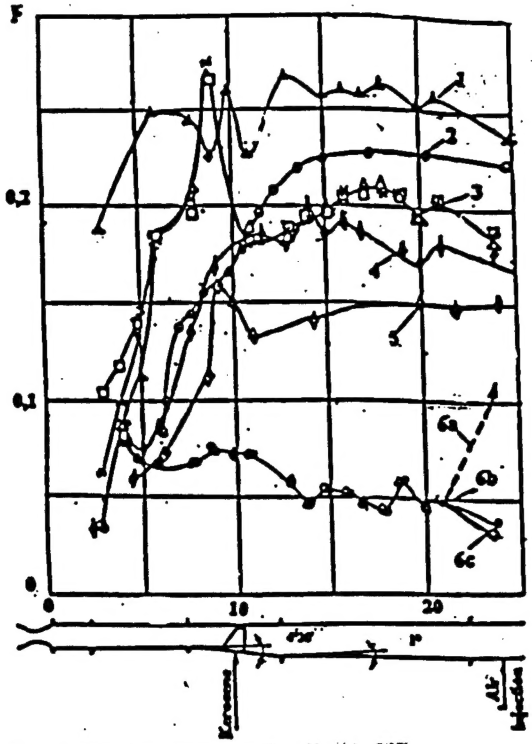


Fig.8. Static pressure distribution along combustor 2 (regimes designation in the Table 2)

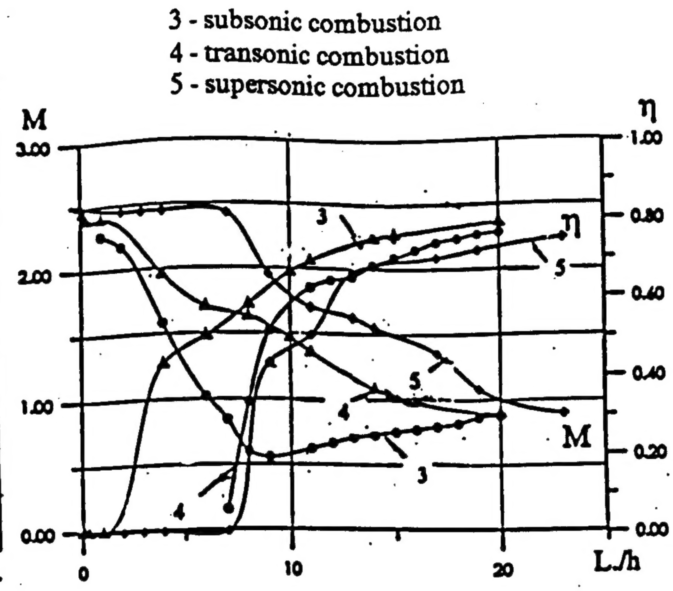
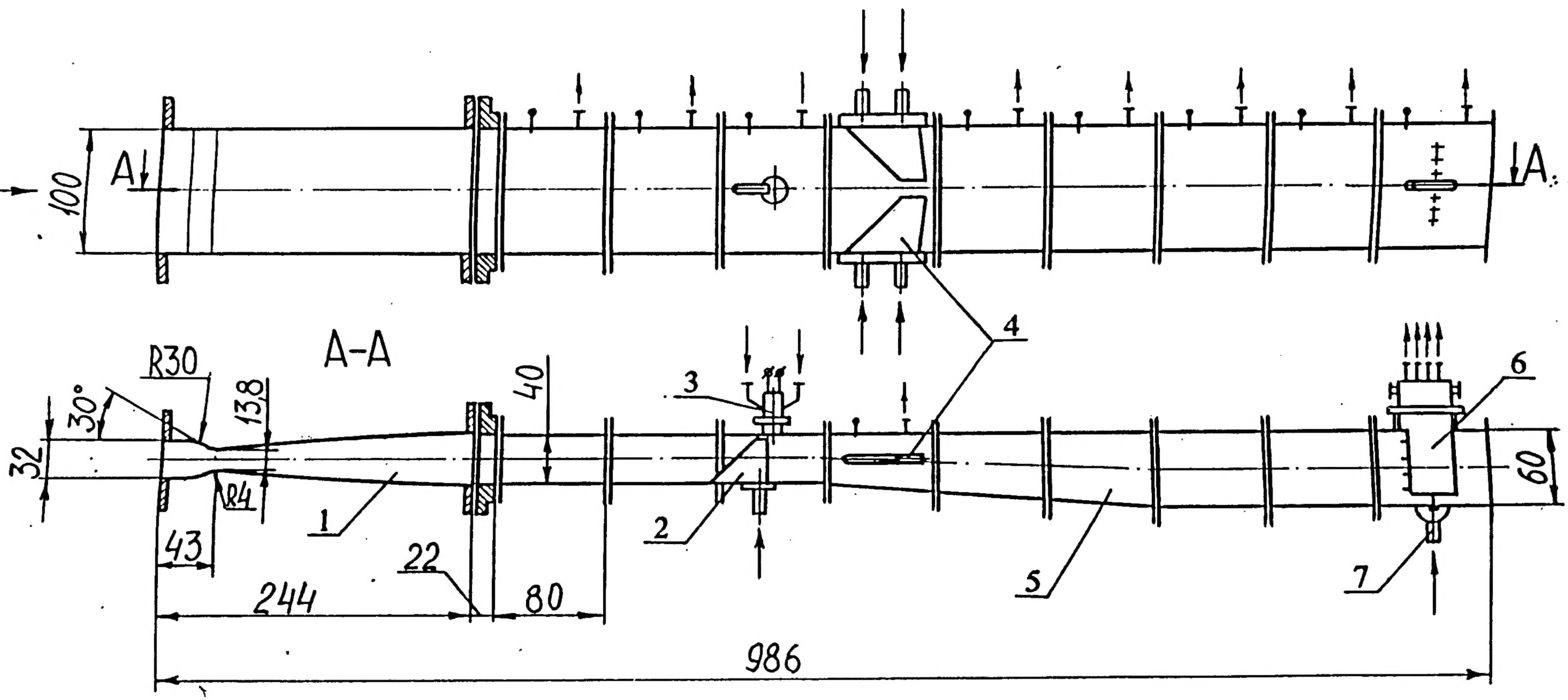


Fig.9. Flow Mach number and combustion efficiency distribution along combustor for characteristic regimes of scramjet combustor operation (regimes 3, 4, 5 of Fig.8)

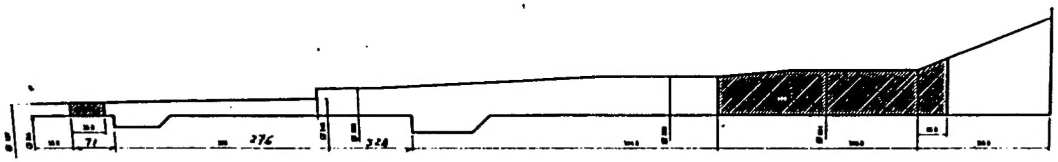
Table 2

№	Operation mode		To, K	Po, MPa	α	Pinj, MPa
1	Subsonic combustion with throttlig	▲	1447	2.87	1.93	11.65
2	Pseudo-shock flow mode without fuel struts and combustion	◒	2200		1.0	
3	Subsonic combustion with frontal block of struts	△ ✱ □	1437 1369 1341	2.86 2.77 2.76	1.94 1.91 1.90	0 0 0
4	Transonic combustion with 3 echeloned struts	♦	1560	2.84	1.58	0
5	Supersonic combustion with 5 echeloned struts	◊	1440	2.57	1.34/1.76	0
6a	Regime with fuel feed into strut block and duct throat choking by cold air.	▲	1447	2.87	1.93	11.65
6в	Regime with duct blow-through and fuel feed into strut block until ignition moment	●	1381	2.81	∞	0
6c	Cold regime with duct blow-through with cold air feed into strut block instead of fuel.	○	1319	2.73	∞	0

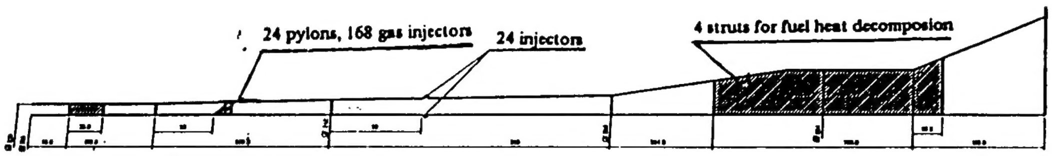


1. Supersonic nozzle M=2.5
2. Pilot injector
3. Plasma igniter
4. Fuel struts
5. Channel combustion chamber
6. Comb of Pitots
7. Air-jet throttle

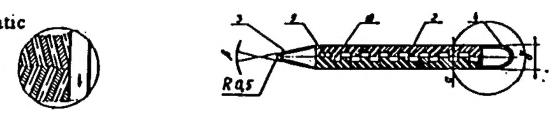
Fig.10. Test facility for experimental study of ignition and combustion stabilization of various hydrocarbon fuels in gaseous phase



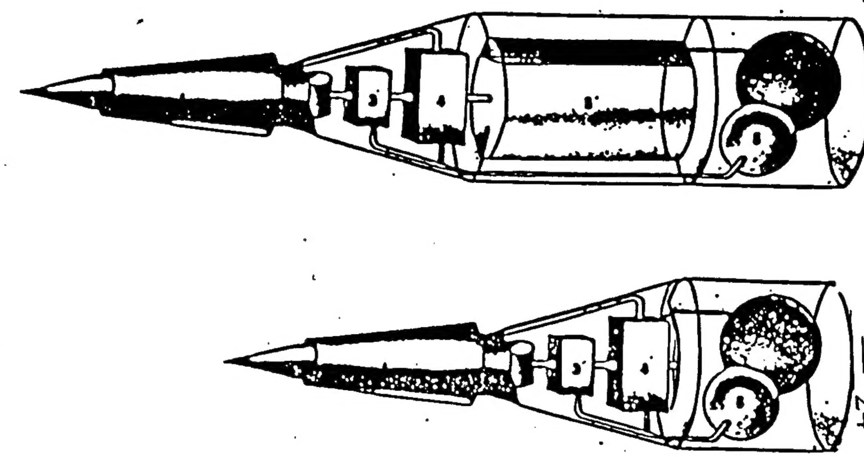
Hydrogen fueled scramjet duct (original)



Fuel decomposition products removal schematic

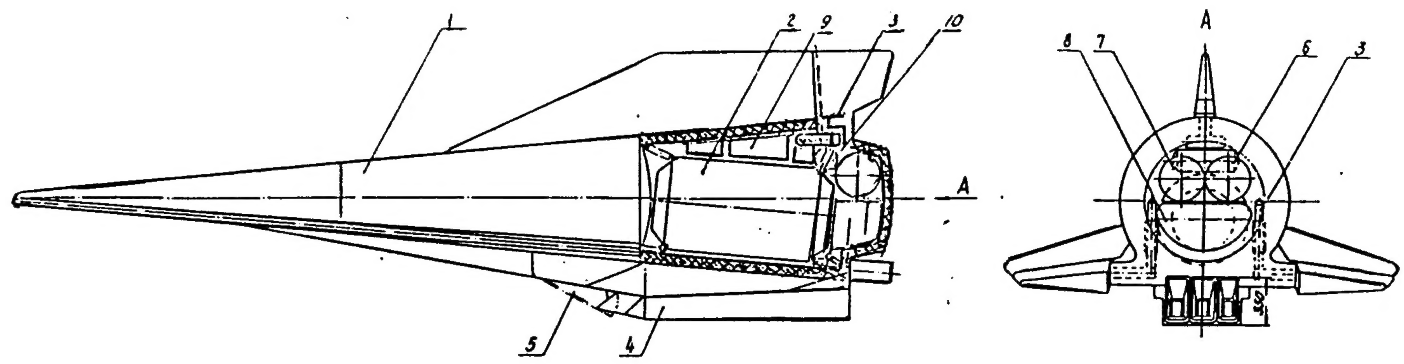


Hydrocarbon fueled scramjet duct (modified)



	H/C	L_{H_2}
Flight Mach number	6,5	6,5
Onboard fuel weight, kg	<50	17
Mass, kg	465	595
Length, m	3,2	4,3
Diameter, m	0,75	0,75

Fig.11. "Kholod" HFTB versions



1. HFTB
2. Liquid hydrogen tank
3. HFTB rudder unit
4. Scramjet
5. Flap

6. Spherical bottle (nitrogen)
7. Spherical bottle (helium)
8. Parachute container
9. Telemetry system equipment
10. Pressurized feed system

Vehicle length, mm	6284
Wing span, m	3000
Wing carry surface, m^2	11,1
Area of elevon, m^2	0,78
Area of rudder, m^2	1,14
Yawing angle of wing	75°55′

C_9H_{20}

	$M_f = 6$			$M_f = 8$		
$\alpha_{vehicle}$	0°	4°	8°	0°	4°	8°
G_{air}, kg/s	3.017	4.055	4.923	2.897	4.853	4.999
G_{fuel}, kg/s	0.101	0.122	0.132	0.193	0.210	0.333
α_{comb}	2	2.2	2.5	1	1	1
R_m, kg	111.2	145.6	163.7	160.14	244.20	308.70
I_{sm}, 1/s	1101	1194	1240	836.3	904.5	927.2
	$M_f = 10$					
	$\alpha_{comb} = 0,8$			$\alpha_{comb} = 1$		
$\alpha_{vehicle}$	0°	4°	8°	0°	4°	8°
G_{air}, kg/s	2.837	4.063	4.912	2.837	4.063	4.912
G_{fuel}, kg/s	0.237	0.338	0.409	0.189	0.271	0.328
R_m, kg	138.8	213.5	258.7	119.8	186.6	225.5
I_{sm}, 1/s	585.7	631.6	632.6	634.1	688.6	687.9

I_{sp} - specific impulse determined with completed expansion nozzle, Γ_c=0.97
R_m - single module thrust

Flight distance estimate with hydrocarbon fuel

Fuel				
C_9H_{20}	M_f	6	8	10
	α_{engine}, kg/s	2.2	1	1
	G_{fuel}, kg/s	0,488	0.420	0.813
	τ_{engine}, s	450.7	523.8	270
	L, km	811	1257	812
JP-7	α_{engine}, kg/s	1.4	1.1	
	I_{sm}, 1/s	1100	6000	
	L, km	747	834.3	
CH_4	α_{engine}, kg/s	1.4	1.1	
	I_{sm}, 1/s	1256	884.5	
	L, km	853	1185	
C_8H_{18}	α_{engine}, kg/s	1.6	1.1	
	I_{sm}, 1/s	1374	9314	
	L, km	933	1298	

It is taken in estimate:
m_{fuel}=220 kg, $m_{vehicle}$=2000 kg, μ=0.89, K=3, R=600 kg, $\alpha_{vehicle}$=4°, q=50 kPa

Fig.12. Performance estimate for "IGLA" HFTB scramjet burning hydrocarbon fuels (without change of scramjet flow passage and aerodynamic characteristics of the vehicle)